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Ultrasound Evaluation of Dynamic Responses of Female Pelvic Floor Muscles

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Abstract

Ultrasound imaging of the pelvic floor carries diagnostically important information about the dynamic response of the Pelvic Floor Muscles (PFM) to potentially incontinence-producing stress, which can not be readily captured and assimilated by the observer during the scanning process. We presented an approach based on motion tracking to quantitatively analyze the dynamic parameters of PFM on the Ano-Rectal Angle (ARA). Perineal ultrasonography was performed on 22 asymptomatic females and 9 Stress Urinary Incontinent (SUI) patients with a broad age distribution and parity. The ventral-dorsal and cephalad-caudad movements of the ARA were resolved and kinematic parameters, in terms of displacement, trajectory, velocity and acceleration were analyzed. The results revealed the possible mechanisms of PFM responses to prevent the urine from incontinence in fast and stress events. The statistical analyses showed the PFM responses of the healthy subjects and the SUI patients are significantly different in both the supine and standing experiments.

Keywords

Cough; Dynamic Responses; Motion Tracking; Urinary Incontinence

INTRODUCTION

Stress Urinary Incontinence (SUI), affects 6-33% of the female population and while not life threatening, can severely compromise quality of life as well as imposing a financial burden on the health care system (Delancey 2005). With the advent of Magnetic Resonance Imaging (Christensen et al. 1995; Miller et al. 2004) and Dynamic Ultrasound Imaging technologies (Dietz 2004; Dietz et al. 2003; Miller et al. 2001; Peschers et al. 2001; Sartore et al. 2003) there have been recent advances in the understanding of the anatomical changes occurring in the Pelvic Floor Muscles (PFM) as a consequence of contraction. However there is still a lack of general consensus, especially relating to the role the PFM have within the continence mechanism.

Dynamic visualization of the kinematic characteristics of urogenital structures to stresses that are likely to produce incontinence, such as coughing, could provide important information defining the function and effectiveness of the PFM. Historically dynamic ultrasound imaging

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and quantitative evaluation of urogenital structures during a cough have been limited to the observations and measurement of the bladder neck at rest, and then again at the end of the cough. (Costantini et al. 2006;Howard D et al. 2000;Pregazzi et al. 2002;Tunn et al. 2005). In a previous study we considered the feasibility of analyzing consecutive frames of the captured images to map out the trajectory of urogenital structures during manouvers. We hoped that we could then extract data to define new quantitative parameters of PFM function. (Peng et al. 2006).

To this end we quantitatively evaluated the response of the PFM to the cough reflex of women specifically recruited for evaluation. The readily visible, clearly resolved anatomical structure in perineal ultrasound imaging is the angle the rectal ampulla forms with the anal canal, the ARA. The ARA has become the target of our present analysis because the central sling component of the PFM, puborectalis and pubococcygeus, wrap around the anorectal junction, and its displacement is closely associated with a PFM contraction (Costantini et al. 2006;Huang et al. 2006).

In the absense of any existing quantitative values identifying the response of the ARA to the cough reflex, we have defined a new set of parameters, that can be measured directly from ultrasound imaging and are potentially a useful diagnostic determinant of PFM function. Based on the measured values of displacement and time, we were able to derive relevant additional kinematic parameters in terms of trajectory, velocity and acceleration of travel of the ARA in the supine as well as the standing position stimulated by the reflex contraction of the PFM.

MATERIALS AND METHODS

Subjects

Data were obtained from a total of 31 volunteers, recruited according to a protocol approved by the Stanford University IRB committee. The investigators were blinded to the continence state of the volunteers, who after evaluation, were divided on the basis of history and self reported symptoms to controls: defined as no reported incontinence and to those with Stress Urinary Incontinence (SUI). The mean and Standard Error (SE) of the age of 22 controls was 39.0 ± 2.3 years, (parity range: 0~3) and of 9 SUI women 47.9 ± 4.4 years, (parity range: 0~2). The criteria for exclusion were: absence of previous genitourinary surgery and no current pharmacotherapy for over-active bladder. All women were given an oral description of the methodology to be followed, had a mailed narrative of the principles of PFM function and gave witnessed written informed consent to actively participate in this procedure.

Imaging Procedure

To ensure adequate bladder volume for imaging, a standardized approach was taken; where volunteers were asked to void 1hour before testing, then drink 16floz (450mls) of water and to refrain from voiding until after the test sequences. A preliminary digital vaginal examination assessed the ability of the volunteers PFM to contract their PFM during voluntary and reflex contractions. Volunteers were initially imaged using a Hitachi EUB-52 ultrasound scanner (Hitachi, Japan) connected to a 128 element high definition linear array operating at 3.4-5.0 MHz. The ultrasound transducer was covered in ultrasound gel, covered by a glove and then more ultrasound gel was applied before being placed on the perineum in a mid sagittal orientation, orientating the transducer so that the clearest images of the bladder, urethra, ARA and Symphysis Pubis (SP) were viewed. The probe was applied with sufficient skin pressure to maintain the location and orientation of the urogenital structures, without distorting the pelvic structures. To keep the out-of-plane rotation of the ultrasound transducer in an acceptable range ($< \pm 5^\circ$), a six degrees-of-freedom measuring device a Flock of Birds, (FOB) (Ascension technology Corporation VA, USA) shown in Fig. 1 was used. We fixed the FOB on the handle

of the ultrasound probe and the orientation (azimuth, elevation and roll angles) of the ultrasound transducer was visualized in real-time during scanning. All volunteers were then asked to cough on command while imaging, in supine crook lying position and if time allowed in standing too. An average of three consecutive coughs was elicited. The timing of the cough was registered by recording the sound intensity simultaneously with the imaging data using a microphone: Plantronics Audio™ 60 stereo PC (Plantronics, CA, USA) headset placed at the foot of the examination couch on a fixed hook.

Video recordings of the imaging and audio signals were recorded on a PC using a USB capture card and stored uncompressed in AVI format for off line analysis. Valid ultrasound data of 22 continent women and 9 SUI women were acquired in supine and 18 continent women and 4 SUI women were acquired in the standing position. The size of the ultrasound image was 320×240 pixels at 8-bit resolution at a rate of 30 frames per second. Analysis of video data was done using a 2 CPU HP workstation using MATLAB 7.1 software.

Coordinate system

An orthogonal coordinate system fixed on a bony landmark, the SP, was established (Fig. 2). The two axes of the coordinate system are parallel and vertical to the urethra at rest respectively. The coordinate system is fixed during the maneuver, so when the subject deforms the bladder (State 2 in Fig. 2), the coordinate system will maintain its original position and the ensuing trajectory of urogenital structures can be measured relative to this fixed axis.

Visual examination of the ultrasound images suggests that the displacement of the ARA during maneuvers contains components that can best be defined as a ventral (anterior) component towards or dorsal (posterior) component away from the SP and a cranial (superior) component upwards or caudal (inferior) component downwards. This scheme is supported by other studies that suggest that in a functional PFM contraction, the bladder neck moves cranio-ventrally (Miller et al. 2001) increasing the closure pressure within the urethra as it is displaced towards the SP (Bump et al. 1991; Theofrastous et al. 1997) and during valsalva, as the IAP increases, the bladder neck moves in an dorsal-caudal direction (Howard D et al. 2000).

Motion tracking algorithms

In order to accurately map the trajectory of the ARA in response to a cough it is necessary to maintain each frame indexed to the SP, which is a stationary, rigid, non deforming structure. However, the movement of the ultrasound probe in experiments could cause a motion artifact in the image of the SP. The motion artifact of the SP needs to be tracked and subtracted from the motion of the ARA, therefore an adaptive motion tracking algorithm based on matching template was developed to measure the movement of the SP.

Initially, a template of the SP is manually defined in the first frame of the ultrasound video. The template is then compared with the second image frame with different offsets in both x and y direction. The matched position in the second image frame is defined as the position where the difference function $D(k,l)$, given by Eqn. (1), has the minimum value. The function of difference $D(k,l)$ is defined as:

$$D(k, l) = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} |T_{i,j} - P_{i+k, j+l}| \quad (1)$$

where, $T_{i,j}$ and $P_{i+k, j+l}$ are the template and the image to be matched respectively. M and N is the size of the template. k and l are offsets for matching at different position.

The template for the matching the following image frames is then updated according to Eqn. (2) and the matching procedure is repeated until the last image frame.

$$T(n) = \frac{1}{n} \sum_{i=0}^{n-1} S(i) = \frac{n-1}{n} T(n-1) + \frac{1}{n} S(n-1) \quad n \geq 2 \quad (2)$$

where, $S(i)$ is the matched position of the SP in image frame i .

A similar adaptive matching algorithm is developed to track the motion of ARA. However, ARA is a soft tissue structure which deforms, particularly in fast maneuvers like coughing. Therefore, a weight coefficient is introduced to speed up the updating of the template in order to follow the deformations:

$$T(n) = w \cdot T(n-1) + (1-w) \cdot S(n-1) \quad n \geq 2 \quad (3)$$

where, w is the weight coefficient, $w \in [0,1]$. In practice, w is set to a value between 0.7 and 0.8 according to the extent of the ARA deformation. To decrease the effect of the size and position of the initial template, manually defined in the first image frame, the tracking procedure is performed four times with different initial templates and the results are averaged. The relative movement of ARA to the SP is then derived by subtracting the motion of SP from that of ARA.

Kinematic parameters and Statistical analysis

Following the motion tracking of the SP and ARA, the movement of the ARA is decomposed into the two orthogonal components. Fig. 3 illustrates the magnitude of displacement in the two directions together with the audio signal used to mark the onset of a cough.

To compare the magnitude and timing of the ARA movement of the continent women and SUI women, the displacement signals from different women needed to be synchronized to a same time point in the coughs. For the purpose of studying the dynamic responses of the PFM to a cough, we chose a reference point that was visible in all volunteers, that is when the ARA had maximum caudal displacement during the cough. The reference point for synchronization (SP) is marked by the dashed lines in Fig. 3.

Displacement signals derived from each cough episode were differentiated to generate the velocity of displacement, and the second derivative was computed to generate the acceleration values. The resulting values of velocity and acceleration were smoothed using an 8-order Butterworth low-pass filter (cutoff frequency=3Hz) and the filtered velocity and acceleration signals were used to graphically represent the data. Mean and SE of the displacement, velocity and acceleration were calculated and presented graphically.

Statistical comparisons, using the T-test, were performed to evaluate the level of significant differences of the displacement and acceleration components at the synchronization point and to compare the effects of a change, between standing to supine within each group.

To study the velocity response of the PFM to the inevitable increase of IAP created during a cough, the timing of the cough is divided into two time periods, 0.5s before the synchronization point ($T_{0.5\text{Before}}$) and 0.5s after the synchronization point ($T_{0.5\text{After}}$) (Fig. 6a and Fig. 8a). The average velocities in both periods are analyzed.

RESULTS

Motion tracking of the SP and ARA

Fig. 4 illustrates the results of the motion tracking of a continent woman's SP and ARA in supine. Fig. 4 (a) shows the ultrasound image at rest and the cranio-ventral coordinate system. The motion tracking of the SP and ARA are shown in Fig. 4 (b) and (c) respectively. The relative movement of ARA, shown in Fig. 4 (d), is derived by subtracting the motion of SP from that

of ARA and then transforming the image coordinate system to the cranio-ventral coordinate system.

Displacement and trajectory of the ARA in supine

Fig. 5 (a) illustrates the differences between continent and SUI women in the magnitude and ventral-dorsal and cranio-caudal displacement during a cough. As clearly indicated by Fig. 5 (a), both the direction and temporal sequence between the continent and SUI women are distinctly different. Thus during a cough, in continent women the ARA moves ventrally towards the SP. In SUI women the ARA moves dorsally away from the SP. Furthermore, the amplitude of the maximum caudal movement of the SUI women's ARA is larger than that of the continent women.

Table 1 shows Mean and SE of the displacement of the ARA at the synchronization point. T-tests were performed to compare the continent and SUI women. The results indicate that the ARA displacements of the continent and SUI women are significantly different ($P < 0.0001$) in both the ventral-dorsal and cranio-caudal directions.

While Fig. 5 (a) clearly illustrates the temporal sequence of the amplitude of the displacement in the given orientation, it does not show the exact pathway followed by the ARA before, during and after the cough. In order to better represent the comparison between the different movement modes of the continent and SUI women, the trajectory of the ARA movements are plotted on a polar coordinate system shown in Fig. 5 (b).

Fig. 5 (b) demonstrates that the ARA trajectories of the continent women are distinct from those of the SUI women during a cough. The ARA has a small ventral movement before a caudal movement then returns to the initial starting position. In contrast, the ARA of SUI women moves only in a dorso-caudal (back and down) direction during the cough and returns to the original position after the cough.

Velocity and Acceleration in supine

Fig. 5(a) shows that the time course of the displacements, measured in each direction are distinctly different between continent and SUI women. These differences were further analyzed by evaluating the velocity and acceleration produced by the cough. The velocities are illustrated by Fig. 6 (a), which shows that the velocity of the ventral movement of the continent women reach the maximum before the synchronization point. Conversely, the velocity of the ventral movement of the SUI women reaches the maximum after the synchronization point.

To better characterize the velocity at which the ARA is displaced and released in coughing, the velocity in the 0.5s preceding the synchronization point ($T_{0.5\text{Before}}$) and 0.5s after the synchronization point ($T_{0.5\text{After}}$) are averaged and analyzed separately. Table 2 shows the velocity of the ARA averaged during $T_{0.5\text{Before}}$ and $T_{0.5\text{After}}$.

Statistical analysis shows that the ARA velocities of the continent and SUI women are significantly different during $T_{0.5\text{Before}}$ and $T_{0.5\text{After}}$. In the 0.5s before the synchronization point, the continent women have a ventral velocity, towards the urethra and pubic bone, whereas the SUI women have a dorsal velocity, away from the urethra. The caudal velocity of the ARA in the SUI women is also significantly higher than that of the continent women during this time frame. Furthermore, the ventral and cranial velocities of the ARA of the SUI women are significantly higher than those of the continent women during the 0.5s after the synchronization point.

The acceleration of the ARA, shown in Fig. 6 (b), suggests that the continent and SUI women have disparate acceleration in the ventral-dorsal direction and similar acceleration in the cranio-

caudal direction. Table 3 shows acceleration of the ARA at the synchronization point comparing SUI with continent women. The results show that the ventral-dorsal acceleration of the ARA of the continent and the SUI women are in opposite directions. In the cranio-caudal direction, the difference between the ARA acceleration of the continent women and SUI women is slower, but not statistically significant.

Displacement and trajectory of the ARA in standing

Ventral-dorsal and cranio-caudal displacements of the ARA in standing, displayed in Fig. 7 (a), show the SUI women have more movement in both the ventral-dorsal and cranio-caudal directions compared to the continent women. Fig. 7 (a) also shows that the ARA of the continent women initially moves ventrally, before moving dorsally.

Table 4 shows displacement of the ARA at the synchronization point in standing, comparing the continent women and SUI women. The results show SUI women have significant more dorsal and caudal displacement than the continent women.

Fig. 5 (a) and Fig. 7 (a) indicate that the ARA movements in supine and in standing are unlike. The ARA displacements at the synchronization point in supine (Table 1) and in standing (Table 4) are compared. For the continent women, both the ventral-dorsal and caudal displacements in supine and in standing are significantly different ($P=0.02$ and $P=0.006$ respectively). In supine, the ARA of the continent women moves cranio-ventrally ($0.18\pm0.05\text{cm}$ and $-0.59\pm0.04\text{cm}$) at the synchronization point. In contrast there is less ventral-dorsal and caudal movements in standing ($0.01\pm0.04\text{cm}$ and $-0.40\pm0.05\text{cm}$ respectively). For the SUI women, there is significantly more dorsal displacement ($P=0.0004$) in standing ($-0.88\pm0.23\text{cm}$) than in supine ($-0.21\pm0.05\text{cm}$).

The trajectory of the ARA movements, displayed in Fig. 7 (b), illustrates the differences between the continent women and the SUI women. The ARA trajectory of the continent women can be considered in three stages. During the first stage (A) there is a caudal displacement of the ARA, followed by a cranio-ventral (stage B) shift and finally during stage C, the ARA moves dorsally back towards its starting position. The ARA trajectory of the SUI women has only two stages. Firstly, the ARA moves in a dorsalcaudal direction before moving back cranio-ventrally to its original starting position.

Comparison of Fig. 5 (b) and Fig. 7 (b) demonstrates the differences of the ARA trajectories in supine and in standing. For the continent women, the trajectory in supine and standing are dissimilar. In supine, the ARA has no dorsal displacement and more caudal movements. For the SUI women, the trajectory in supine and standing are comparable, although there is more dorsal movement in standing than in supine.

Velocity and Acceleration in standing

The ARA velocities in standing are illustrated in Fig. 8 (a), indicating that the velocity of the ARA in continent women is very close to zero before the synchronization point. On the contrary, the SUI women have a high dorsal and caudal velocity before the synchronization point.

The velocity of the ARA in standing was also analyzed in the 0.5s before and 0.5s after the synchronization point. Table 5 shows Mean and SE of the velocities of the ARA averaged $T_{\text{Before}0.5}$ and $T_{\text{After}0.5}$. Comparing the continent women and SUI women shows that the SUI women have significantly higher velocities than the continent women during both time frames.

In Table 6, the ARA velocities in supine (Table 2) and in standing (Table 5) are compared showing that in continent volunteers, the ventral-dorsal velocities are different from supine to

standing. In supine, the continent women have a ventral velocity during $T_{0.5\text{Before}}$ and a dorsal velocity during $T_{0.5\text{After}}$. However in standing, the ventral velocity is kept after the synchronization point. In addition, in standing, the caudal (downward) velocity during $T_{0.5\text{Before}}$, and the cranial (upward) velocity during $T_{0.5\text{After}}$ significantly decreases in the continent volunteers. For the SUI women, the dorsal $T_{0.5\text{Before}}$ and ventral $T_{0.5\text{After}}$ velocities significantly increase when in standing compared to supine, while the cranial and caudal velocities do not change significantly.

Table 7 shows the acceleration of the ARA at the synchronization point in standing comparing the continent and SUI women. The results suggest that the SUI women have a higher but non significant difference in acceleration in both directions.

The statistical test comparing the ARA accelerations in supine (Table 3) and in standing (Table 7) show that ARA accelerations of the continent women at the synchronization point in supine and in standing are significantly different. In standing, the ventral-dorsal acceleration is reversed to that in supine ($P=0.01$) and the craniocaudal acceleration is significant lower ($P=0.03$) than that in supine. For the SUI women, the accelerations in the ventral-dorsal and cranio-caudal directions are not significantly different ($P=0.83$ and $P=0.41$ respectively).

DISCUSSION AND SUMMARY

The automated method of motion tracking the ARA is able to quantify dynamic parameters of PFM function that have not been previously analyzed using dynamic ultrasound imaging. Analysis of the displacement and trajectory of the ARA movement in supine and standing imply that the PFM of the continent women function very differently from those volunteers with SUI. It appears that the functional PFM in continent women, provide support to the urogenital structures prior to and during a cough, acting like a brake, to resist or limit the dorsal-caudal movement that occurs as IAP inevitably rises during a cough. In women with SUI, this PFM “brake” appears to have been applied late, or is diminished, demonstrated by the increased displacement of the ARA and the increased velocity and acceleration. Research using kinesiological EMG also supports our 2D ultrasound analysis. In continent women there is recruitment of PFM motor units (Deindl et al. 1993) and an increase in intra-urethral pressure (Constantinou & Govan 1982) prior to an increase in intra-abdominal pressure (IAP) during a cough. However there are altered PFM activation patterns during a cough, measured by EMG in women with SUI compared to healthy volunteers (Deindl et al. 1994), with shorter activation periods, lack of response or paradoxical inhibition.

In standing, our results suggest that the functional PFM are already activated, so that the overall displacement, cranial-caudal velocity and acceleration of the ARA during a cough in standing are reduced when compared to the supine lying position. These observations are supported by conclusions drawn by Morgan et al. 2006 suggesting that vaginal closure force increases with a change in posture because of higher IAP and greater resistance in the PFM (Morgan et al. 2005). These phenomena were not evident in our group of SUI women, where the overall displacement, velocity and acceleration in a ventral-dorsal direction increases while standing compared to supine.

Our results suggested that the PFM do provide an active role to the continence mechanism, by providing active support at the appropriate time to the urogenital structures during coughing as shown in Fig. 6 and 8. During a cough, the ARA of the continent women moves ventrally towards the urethra providing the urogenital structures with support, before moving dorsally presumably due to the increase in IAP. The lack of initial ventral movement is lost in most women with SUI indicated by the dorsal trajectory of displacement of the ARA, prior to rebounding back in a ventral direction with higher velocity. Dorsal displacements of urogenital

structures are likely to reduce the closure pressures in the urethra and therefore increase the possibility of urinary incontinence. Our results suggest that appropriate timing control of the PFM contraction may be as important as the amplitude of the pressures produced by the PFM contraction in preventing SUI. In addition it appears that postural support during standing is a normal PFM function which is lost in women with SUI. However our sample size of SUI women in standing was small, so the results should be interpreted with caution.

In order to give greater understanding of the continence mechanism, in future studies it will be useful not only to track the trajectory using ultrasound, but to compare this with the onset of PFM activity by EMG and changes in IAP during a cough. Furthermore, standardizing bladder volume (Dietz & Wilson 1999) and tidal volume of the cough will clarify whether parameters other than SUI influence the trajectory taken by the ARA.

Although we used a 3D tracking device to keep the out-of-plane rotation of the ultrasound transducer in an acceptable range, 2D ultrasound imaging is unable to analyze out-of-plane structures and the accuracy of the image analysis will be affected. More definitive anatomical identification of the mechanisms involved in response to the cough reflex could potentially be made using 3D ultrasound imaging. However current 3D imaging techniques are not fast enough to record the timing of the ARA movement in maneuvers such as coughing. Predictably 3D imaging is cost prohibitive for the majority of clinicians so it is anticipated that 2D ultrasound will be, for the foreseeable future, the measuring and feedback tool of clinical choice. Clearly as evidenced by the present study, there is still potential for new parameters and quantification to be made using 2D ultrasound.

In clinical practice, observations, whether made manually by palpation, or observed during video cystography or ultrasound imaging infers that urethral hypermobility is associated with SUI. While we did not specifically evaluate urethral mobility, a subject to be reported in a separate study, our results indicate that the mobility detected at the level of the ARA may be consistent and comparable with observations of urethral mobility. Ultrasound scanning by tracking bladder neck motion (Dietz et al. 2002; Pregazzi et al. 2002; Schaer et al. 1999) is a well-established means of obtaining dynamic images of the lower urinary tract, can be readily combined with the visualization of the ARA to acquire a better understanding of mechanism of the urinary continence of the whole pelvic floor.

We quantitatively demonstrated the characteristic mechanical response of the ARA to the cough reflex of asymptomatic women. Evidence was provided to show that continent and asymptomatic women can clearly and significantly be identified from those with SUI on the basis of a number of parameters. Furthermore these studies were obtained using the non-invasive nature of transperineal ultrasound, the significance of the results are of current practical clinical value in evaluating women with SUI. As a consequence of the degree of the analytical treatment applied to the temporal sequence of the data, important aspects of the role of the PFM function was gained. Such information may prove critical in identifying the contribution of the derived parameters to the mechanisms of continence.

In defining the displacement parameters a specific coordinate system was used in such a way as to identify the horizontal and vertical components of distance, and direction of the trajectory. We are able to intuitively visualize the position of ARA and define its dynamic components of velocity and acceleration. Our approach is one of the first studies enabling quantification, generating new parameters of PFM function. It incorporates original software, which is less operator dependent, thereby improving the reliability of the measurement tool.

Finally our approach of processed Ultrasound imaging of the pelvic floor provides significant new information relating to its dynamic response to stress. This non-invasive type of information is potentially of use in understanding the mechanisms of urinary continence, which

is a silent epidemic severely affecting the quality of life of women with Urinary Incontinence. It is hoped that this study can help lay the foundations of determining a more reliable pragmatic assessment of PFM function and eventually improve the rehabilitation of women with SUI and other pelvic floor disorders.

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(a)

(b)

Fig 1.
 (a) The ultrasound probe fixed with a FOB system. (b) Typical rotation of the ultrasound probe in experiments (rotation angles $< \pm 5^\circ$).

Fig 2.

The orthogonal coordinate system fixed on the SP. The two orthogonal components (ventral-dorsal and cranial-caudal components) of the ARA displacement reflect PFM functions of squeezing the urethra and supporting the bladder respectively.

Fig 3. Typical ventral-dorsal and cranio-caudal displacements of the ARA in coughing. The displacements of the ARA are shown relative to the audio recording of the subject's cough. The signals from the continent women and the SUI women are shown in the left and right panels respectively.

Fig 4.

Results of the motion tracking of a continent women's ARA and SP in supine. (a) The ultrasound image and the coordinate system. The motion tracking of (b) the SP and (c) the ARA. (d) The ventral-dorsal and cranio-caudal components of the displacement of the ARA.

(a)

(b)

Fig 5.

(a) Ventral-dorsal and cranio-caudal displacements of the ARA in supine. The SEs of the displacements are marked by the colored areas. (b) Trajectory of the movement of the ARA in supine. The continent and the SUI women are shown in green and red respectively.

(a)

(b)

Fig 6. Ventral-dorsal and cranio-caudal components of the (a) velocity and (b) acceleration of the ARA in supine. The continent and the SUI women are shown in green and red respectively. The SEs of the signals are marked by the colored areas.

(a)

(b)

Fig 7.

(a) Ventral-dorsal and cranio-caudal displacements of the ARA in standing. The SEs of the displacements are marked by the colored areas. (b) and (c) are the ARA trajectories of the continent women and SUI women.

(a)

(b)

Fig 8. Ventral-dorsal and cranio-caudal components of the (a) velocity and (b) acceleration of the ARA in standing. The continent women and the SUI women are shown in green and red respectively. The SEs of the signals are marked by the colored areas.

Table 1Displacement of the ARA at the synchronization point in supine (Mean $\pm$ SUI, Unit: cm).

	Ventral-dorsal	Cranio-caudal
Continent women	0.18 $\pm$ 0.05	-0.59 $\pm$ 0.04
SUI women	-0.21 $\pm$ 0.05	-1.00 $\pm$ 0.08
P value	P<0.0001	P<0.0001

Table 2

Mean and SE of the averaged velocity of the ARA in the 0.5s before the synchronization point ($T_{0.5\text{Before}}$) and 0.5s after the synchronization point ($T_{0.5\text{After}}$) in supine (Mean $\pm$ SE, Unit: cm/s).

	Ventral-dorsal		Cranio-caudal	
	$T_{0.5\text{Before}}$	$T_{0.5\text{After}}$	$T_{0.5\text{Before}}$	$T_{0.5\text{After}}$
Continent	0.36 $\pm$ 0.09	-0.11 $\pm$ 0.08	-0.94 $\pm$ 0.07	1.19 $\pm$ 0.06
SUI	-0.15 $\pm$ 0.10	0.55 $\pm$ 0.10	-1.34 $\pm$ 0.15	1.57 $\pm$ 0.14
P value	P=0.001	P<0.0001	P=0.008	P=0.005

Table 3Acceleration of the ARA at the synchronization point in supine (Mean $\pm$ SE, Unit: cm/s²).

	Ventral-dorsal	Cranio-caudal
Continent women	-2.61 $\pm$ 1.55	26.82 $\pm$ 2.06
SUI women	5.90 $\pm$ 3.45	33.93 $\pm$ 3.32
P value	P= 0.01	P= 0.07

Table 4Displacement of the ARA at the synchronization point in standing (Mean $\pm$ SE, Unit: cm).

	Ventral-dorsal	Cranio-caudal
Continent women	0.01 $\pm$ 0.04	-0.40 $\pm$ 0.05
SUI women	-0.88 $\pm$ 0.23	-1.17 $\pm$ 0.24
P value	P<0.0001	P<0.0001

Table 5

Velocity of the ARA in the 0.5s before the synchronization point ($T_{\text{Before0.5}}$) and in the 0.5s after the synchronization point ($T_{\text{After0.5}}$) in standing (Mean $\pm$ SE, Unit: cm/s).

	Ventral-dorsal		Cranio-caudal	
	$T_{\text{Before0.5}}$	$T_{\text{After0.5}}$	$T_{\text{Before0.5}}$	$T_{\text{After0.5}}$
Healthy	0.12 $\pm$ 0.08	0.20 $\pm$ 0.06	-0.68 $\pm$ 0.11	0.82 $\pm$ 0.09
SUI	-1.31 $\pm$ 0.32	1.19 $\pm$ 0.42	-1.86 $\pm$ 0.42	2.05 $\pm$ 0.57
P value	P<0.0001	P=0.0001	P=0.0003	P=0.0004

Table 6

Significance of statistical differences of the ARA velocities in supine and in standing.

	Ventral-dorsal		Cranio-caudal	
	T _{0.5Before}	T _{0.5After}	T _{0.5Before}	T _{0.5After}
Healthy	P=0.05	P=0.006	P=0.05	P=0.0004
SUI	P<0.0001	P=0.05	P=0.15	P=0.27

Table 7Acceleration of the ARA at the synchronization point in standing (Unit: cm/s²).

	Ventral-dorsal	Cranio-caudal
Continent women	3.16±1.37	19.51±2.47
SUI women	7.28±5.30	27.83±8.17
P value	P= 0.28	P= 0.20